OPTIMIZATION OF PARAMETERS OF LASER NON-LINEAR INCLINED CUTTING ON STAINLESS STEEL METAL

ABBAS ALLAWI ABBAS

A project submitted in partial fulfillment of the requirements for the award of the Master of Mechanical Engineering

Faculty of mechanical and manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

JUN 2014

DEDICATION

I would like to present my work to those, who did not stop supporting since I was born, my dear mother, my kind father, my dear brothers especially, “Hussein ” and “Hamed ”, and generally, to all my brothers, sisters. They never hesitate to provide me all the support to push me foreword as much as they can. This work is a simple and humble reply to their goodness that I have experienced over during that time. I did not forget my uncles, aunts, all my friends from Iraq and Malaysia, those whom I love and all those, who have been a great help in the completion of this thesis whether directly or indirectly.

Abbas Allawi Abbas

ACKNOWLEDGEMENT

قال تعالى في محكم كتابه الكريم

وَقُلِ اعْمَلُواْ فَسَيَرَى اللّهُ عَمَلَكُمْ وَرَسُولُهُ وَالْمُؤْمِنُونَ

صدق الله العظيم

الاية ١٠٥سورة التوبة

First and foremost, praise is to Allah, for giving me this opportunity, the strength and the patience to finally complete my thesis, after all the challenges and difficulties. I would like to thank my supervisor, Dr. Sivaprakasam Thamizhmanii for his motivation and most significant contribution to this thesis, to the staff in the Faculty of mechanical and manufacturing engineering.

Words fail me to express my appreciation to my parents, my dear brothers, sisters, whose dedication, and persistent confidence in me, have taken the load off my shoulder.

I would like also to thank the Ministry of Higher Education and Scientific Research in Iraq, Furthermore, I want to thank my friends who have helped and motivated me throughout this journey. May Allah reward them all abundantly, my sincere thanks to all.

Finally, I would like to thank everybody, who played a part in ensuring this thesis would be successfully completed, as well as expressing my apology to those that I could not mention individually here.

Abbas Allawi Abbas

ABSTRACT

The aim of this research is to develop a laser cutting process model that can predict the relationship between the process input parameters and resultant surface roughness; kerf width characteristics. The research conduct is based on the Design of Experiment (DOE) analysis. Response Surface Methodology (RSM) is used in this research, it is one of the most practical and most effective techniques to develop a process model. Even though RSM has been used for the optimisation of the laser process, published RSM modelling work on the application of laser cutting process on cutting material is lacking. This research investigates laser cutting stainless steel to be best the circumstances laser cutting using RSM process. The input parameters evaluated are gas pressure, power supply and cutting speed, the output responses being kerf width, surface roughness. The laser cutting process is one of the widely used techniques to cut thickness material for various applications such as fiber, steel wood fabrication. In the area of laser cutting material,it can be improved drastically with the application of hard cutting. The application of cut on stainless steel for various machining techniques, such as bevel linear and bevel non-linear cutting, requires different cut characteristics, these being highly dependent on the process parameters under which they were formed. To efficiently optimize and customize the kerf width and surface roughness characteristics, a machine laser cutting process model using RSM methodology was proposed.

ABSTRAK

Matlamat penyelidikan ini adalah untuk membangunkan satu model proses pemotongan laser yang boleh meramalkan hubungan antara proses penginputan parameter dan kekasaran permukaan yang terhasil; ciri-ciri lebar alur gergaji. Penyelidikan yang dijalankan adalah berdasarkan Rekabentuk Eksperimen (JAS) analisis. Respons Permukaan Metodologi (RSM) digunakan dalam penyelidikan ini dan ia adalah salah satu teknik yang paling praktikal serta paling berkesan untuk membangunkan satu model proses. Walaupun RSM telah digunakan untuk pengoptimuman proses laser tersebut, terbitan kerja pemodelan RSM atas aplikasi proses pemotongan laser atas pemotong bahan adalah kurang. Kajian ini dijalankan pula bagi mengetahui laser memotong keluli tahan karat menjadi kaedah terbaik untuk pemotongan laser menggunakan proses RSM.Penginputan parameter yang dinilai adalah tekanan gas, bekalan kuasa dan kelajuan pemotongan, sambutan keluaran menjadi lebar alur gergaji, kekasaran permukaan. Proses pemotongan laser adalah salah satu teknik yang digunakan secara meluas untuk memotong bahan yang tebal untuk pelbagai aplikasi, seperti serat, keluli kayu fabrikasi. Dalam bidang laser pemotongan bahan, ia boleh diperbaiki secara drastik dengan aplikasi pemotongan keras. Aplikasi pemotongan pada keluli tahan karat untuk pelbagai teknik pemesinan, seperti serong selari dan serong memotong bukan selari, ini memerlukan ciri-ciri pemotongan yang berbeza justeru ini menjadi sangat bergantung kepada proses parameter di mana mereka telah dibentuk.Bagi mengoptimumkan dan menyesuaikan lebar alur gergaji dan permukaan ciri-ciri kekasaran dengan kecekapan, mesin proses pemotongan laser model menggunakan kaedah RSM telah dicadangkan.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATION

ANNs	-	Artificial Neural Networks
ANOVA	-	Analysis Of Variance
CCD	-	Central Composite Design
CW	-	Continuous Wave
CO_2	-	Carbon dioxide
DC	-	Direct Current
I, V, Y	-	Types of bevel
K/W	-	kerf width
K = 1	-	For an ideal Gaussian beam and
K < 1	-	For real laser radiation.
LBC	-	Laser Beam Cutting
MRA	-	Multiple Regression Analysis Model
N2	-	Nitrogen
Nd:YAG and Yt:YAG	-	Yttrium-Aluminum-Garnet (Crystal) Enriched with Neodymium
O_2	-	Oxygen
OP	-	Optical Microscopy
Psi	-	Pounds per square inch
RF	-	Radio frequency
RSM	-	Response Surface Methodology
SEM	-	Scanning Electrical Microscopy
XRD	-	X-Ray Diffraction

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter describes the research background, problem statement, objectives and scope of the research.

1.1.1 Laser

Laser (Light Amplification by Stimulated Emission of Radiation) is basically a cohesive, convergent and monochromatic electromagnetic radiation beam. Its wavelength ranges from ultra-violet to infrared. It can provide very low to very high power with a precise spot to any substrate type through any medium. Laser is differed from other electromagnetic radiation especially in terms of its cohesion, spectral purity and its straight line propagation. Therefore, it plays an important role in different industries, and used in many applications such as communication, military, medical and others. It is used in wide applications due to several properties such as spatial and temporal coherence, low divergence, high continuous or pulsed power density and mono - chromaticity (Majumdar & Manna, 2003). One of its main applications is its ability to act as a heat source known as Laser Materials Processing (LMP). This feature helps to utilize it in forming, joining, machining, manufacturing, coating, deposition and surface engineering. Due to the advantages of laser over the traditional cutting processes, it is commonly used in machining various types of materials, especially very hard materials in many industrial applications. The fundamental advantages of laser cutting are: no vibration because it is a non- contact process and a low heat input that leads to less distortion and its ability to be controlled numerically.

The parameters of laser cutting process play a main role on the cutting edge quality features. The commercially available lasers for material processing are (Eltawahni et al., 2010):

- Solid state crystal or glass laser – Nd:YAG, Ruby
- Semiconductor laser – AlGaAs, GaAsSb and GaAlSb lasers
- Dye or liquid laser solutions of dyes in water/alcohol and other solvents
- Neutral or atomic gas lasers – He–Ne laser, Cu or Au vapor laser
- Ionized gas lasers or ion lasers – argon. ArC / and krypton .KrC / ion lasers
- Molecular gas lasers – CO_2 or CO laser
- Excimer laser – XeCl, KrF, etc
- Fiber laser-ytterbium

But, there are main obstacles that limit the laser extensive use in applications of routine material processing such as a beam size limitation, high cost of installation and replacement, additional and costly accessories, and need for skilled workers (Majumdar & Manna, 2003).

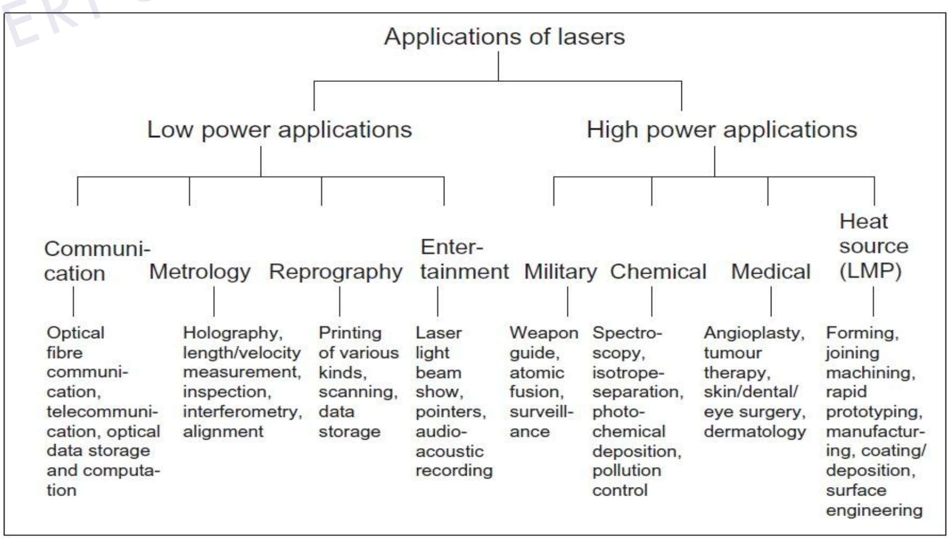

Figure1.1: Application spectrum of lasers (Majumdar & Manna 2003).

1.1.2 Laser Parameters

The laser cutting process quality and the response in terms of cut edge quality is controlled by a number of parameters linked to the laser system, used material, and the cutting process. The laser system parameters are summarized in figure 2 below.

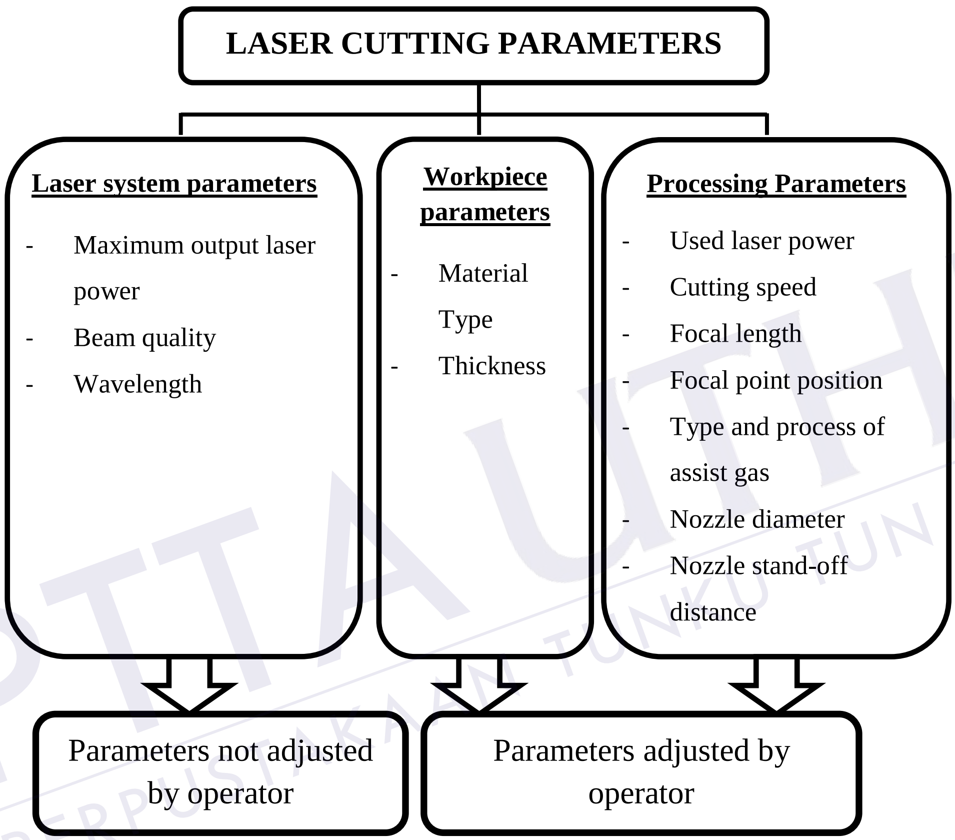

Figure1. 2: Laser Parameters (Wandera, 2010)

Researchers studied the impact of different laser parameters on cut edge quality, kerf dimensions, roughness and surface finish. Karet.al studied the process parameters impacts, such as laser power, spot size and dimensions, and cutting speed on the resulting kerf size. Yilbas (2008) studied the effect of laser power and oxygen gas pressure on the kerf width variation. Ghany and Newishy (2005) indicated a positive relationship between laser cutting quality and the laser power, pulse frequency, cutting speed and focus position.

1.1.3 Laser cut quality characteristics

The laser cut edge characteristics, which can be used to measure the laser cut quality include: the cut kerf width, dross attachment on the lower cut edge, cut edge squareness deviation (perpendicularity), cut edge surface roughness, and boundary layer separation point.

1.2 Problem Statement

The common metal machining is performed by using a laser machine with a vertical cutting head. The literature did not mention and explain the impact of the nonlinear inclined cutting process parameters on the surface quality, and it did not compare this effect with the linear cutting.

The nonlinear inclined cutting is very important in assembling parts or appliances or in welding pieces together as some of the parts and design must have inclined surfaces for ease of their linking and assembling. Therefore, an inclined cutting laser machine should be available, but this machine may not be available because it is expensive. For this reason, the available vertical cutting machine will be used to address this problem, where the incline degree of the work piece will be controlled (usually at an angle of 22˚) under the vertical head to get the inclined cutting. After that the impact of inclined cutting process parameters will be examined on surface quality. This project is focused of an alternative process of the Acetylene oxygen cutting material in the CNC machine. It also focused on their defects on the metal surface, the changing characteristics at a mechanical level, the safety of the surface, the transactions thermal and many more. Therefore, the presence of the CNC laser machine using nitrogen gas best for the safety of the surface, the characteristics of the mechanical and others through the literature review of cutting mild steel, stainless steel and etc.

1.3 Research Objectives

The main objective of this research is to conduct a comprehensive study on the processing parameters effect during an inclined laser cutting of thin sheet stainless steel. The effect of processing parameters is evaluated in terms of the surface's finish and flatness. The research aims to achieve the following objectives:

1. To investigate the laser material processing in inclined cutting.
2. To establish significant design parameters for a high quality of cut.
3. To model the optimal laser processing of a non-linear inclined cutting.

1.4 Research Scope

The aim of this research is to identify the parameters in the inclined laser cutting process that play a major role in producing very low roughness cuts and surface finish, which improve the end product quality. The laser nitrogen assistance will be used for the non-linear inclined cutting process of a thin sheet of stainless steel of 4 mm thickness.

The Response Surface Methodology (RSM) will be applied to construct a mathematical relationship between the laser cutting process parameters, power supply, cutting speed and gas pressure, and between the quality of the responses, namely the quality of cut edge and, and the surface roughness during an inclined cutting process. The potential impact of each laser cutting parameter on the responses will be defined by the verified mathematical models to identify the optimal cutting conditions that lead to the highest quality.

CHAPTER 2

LITERATURE REVIEW

This chapter provides an overview of the laser and laser-cutting machine. The principles of the laser beam generation and the technology involved in the laser cutting machine is presented. The previous studies conducted on lasers and laser-cutting machines were reviewed and suggestions and recommendations from those studies were used in the current study.

2.1 Introduction

The conventional machining use has been restricted because of the sophisticated shape and unusual size of the work material, rigorous design need and the emergence of advanced engineering materials. Thus, the need for nonconventional machining methods becomes an urgent demand which lead to the emergence of Advanced Machining Processes (AMPs). (Choudhury & Shirley, 2010).

Laser machining is one of the AMPs utilized to cut various types of materials economically. Laser beam machining has a wide application because it gives a finer finish to the end product as compared to conventional cutting methods. (Choudhury & Shirley, 2010). Lasers are commonly used to cut or in machine for different types of materials, especially difficult-to-cut materials, in many industrial applications, due to its advantages over the conventional cutting processes. (Eltawahni et al., 2010). Compared with other conventional mechanical processes, laser cutting removes little material, involves highly localized heat input to the workpiece, minimizes distortion, and offers no tool wear. Laser cutting is a thermal, non-contact, and highly automated process well suited for various manufacturing industries where a variety of components in large numbers are required to be machined with high dimensional accuracy and surface finish. (Madic et al., 2012).

2.2 History of laser

The first gas laser was developed in 1961 by A. Javan, W. Bennet, and D. Harriott of Bell Laboratories, using a mixture of helium and neon gases. At the same laboratories, L. F Johnson and K. Nassau demonstrated the first neodymium laser, which has since become one of the most reliable lasers available. This was followed in 1962 by the first semiconductor laser, demonstrated by R. Hall at the General Electric Research Laboratories. In 1963, C. K. N. Patel of Bell Laboratories discovered the infrared carbon dioxide laser, which is one of the most efficient and powerful lasers available today. Later that same year, E. Bell of Spectra Physics discovered the first ion laser, in mercury vapor. In 1964 W. Bridges of Hughes Research Laboratories discovered the argon ion laser, and in 1966 W. Silfvast, G.R. Fowles, and B. D. Hopkins produced the first blue helium-cadmium metal vapor laser. During that same year, P. P. Sorokin and J. R. Lankard of the IBM Research Laboratories developed the first liquid laser using an organic dye dissolved in a solvent, thereby leading to the development of broadly tunable lasers. Beside, W. Walter and co-workers at TRG reported the first copper vapor laser. In 1961, Fox and Li described the existence of resonant transverse modes in a laser cavity. That same year, Boyd and Gordon obtained solutions of the wave equation for confocal resonator modes. Unstable resonators were 9 demonstrated in 1969 by Krupke and Sooy and were described theoretically by Siegman. Q-switching was first obtained by McClung and Hellwarth in 1962 and described later by Wagner and Lengyel. The first mode-locking was obtained by Hargrove, Fork, and Pollack in l964. Since then, many special cavity arrangements, feedback schemes, and other devices have been developed to improve the control, operation, and reliability of lasers.

2.3 Materials for laser cutting

Laser can cut plastics, woods, rubbers, foams, papers, and thin metals as long as they do not contain chlorine. Depending on the material, there is usually no limit to the thinnest sheet that can be cut, and the thickest sheet that can be cut is typically 1" {24 mm}. Also on the same list are some woods, various plastics including acrylic, ABS, Mylar, Delrin, PETG, and styrene, as shown in table1 below.

Table 2.1 Materials for Laser Cutting.

Plastics	• ABS (acrylonitrile butadiene styrene) • Acrylic (also known as Plexiglas, Lucite, PMMA) • Delrin (POM, acetal) – for a supplier, try McMaster-Carr. • High density polyethylene (HDPE) – melts badly • Kapton tape (Polyimide) • Mylar (polyester) • Nylon – melts badly • PETG (polyethylene terephthalate glycol) • Polyethylene (PE) – melts badly • Polypropylene (PP) – melts somewhat • Styrene • Two-tone acrylic – top color different than core material, usually for custom instrumentation panels, signs, and plaques.
Metals materials	Such as aluminum alloys, alloy steel, brass, carbon steel, stainless steel, titanium steel, and tool steel, Chrome, Coated metals, Cobalt, Copper, Gold, Platinum, Silver, Tin , Zinc
Foam	• Depron foam – often used for RC planes. • EPM (Ethylene propylene rubber) • Gator foam – foam core gets burned and eaten away compared to the top and bottom hard shell.
Other	• Cloths (leather, suede, felt, hemp, cotton) • Magnetic sheets • Papers (Such as paper, cardboard, and matte board) • Rubbers (only if they do not contain chlorine) • Teflon (PTFE, Polytetrafluoroethylene). • Woods (MDF, balsa, birch, poplar, red oak, cherry, holly, etc.)

2.4 Laser Principal

The principles of current lasers are the same as the first one developed. A laser beam is generated in a glass tube with a mirror at each end. The laser gas is pumped into the glass and circulated by a turbine. One of the mirrors is 100 percent reflective, and the other is less than 100 percent reflective (usually seventy percent) as shown in Figure 2.1. The laser gas can be a mixture of helium, carbon dioxide and nitrogen. This mixture of laser gas is commonly known as a CO_2 laser. There are several other lasing gas mixtures available and in use, but only for high powered industrial lasers, the CO_2 mixture is the most common. An external energy source, such as the electrical power (most commonly DC power) or radio frequency (RF generator) excites the atoms in the laser gasor radio frequency (RF generator) that in turn, excites the atoms in the laser gas mixture. When the atoms of the laser gas become excited, the stimulated gas atoms give off a photon of 17 lights. This photon excites other atoms of the laser gas giving off more photons. This forms a chain reaction. There are many examples of artists and designers using the laser cutting technology to produce innovative concepts, especially with the use of soft bending - a process that slits cut into the profile to allow for bending by hand (Myers, et al., 2010).

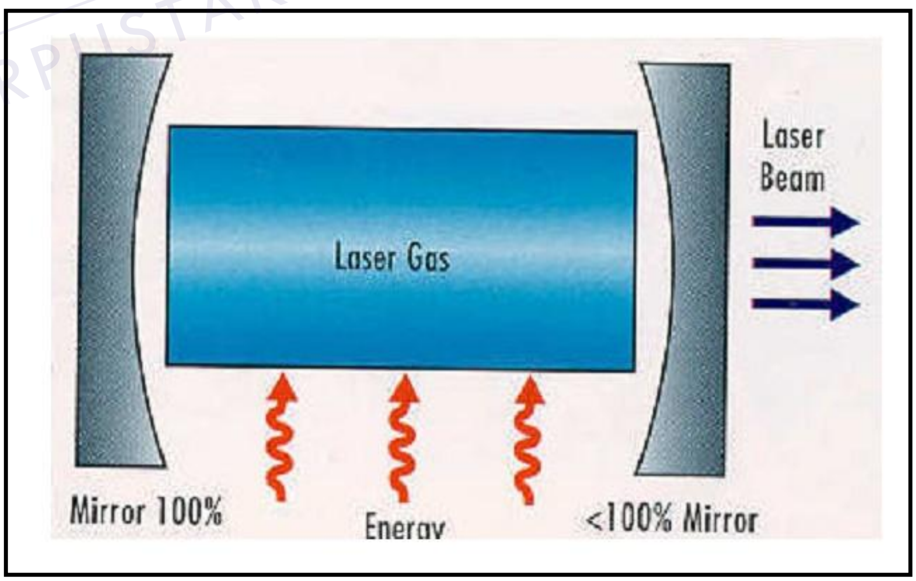

Figure 2.1 Illustration of Laser Working (Myers et al., 2010)

REFERENCES

Ahn, D. G., &Byun, K. W. (2009). *Influence of cutting parameters on surface characteristics of cut section in cutting of Inconel 718 sheet using CW Nd: YAG laser*. Transactions of Nonferrous Metals Society of China, 19, s32-s39

Al-Wedyan H., Demirli K. and Bhat R. (2001).*A technique for fuzzy logic modeling of machining process,* 20th NAFIPS international conference, 5, 3021–3026

Baskoro, A. S., Herwandi, K. G. S., Siswanta, A., &Kiswanto, G. (2011).*Analysis of Cutting Process of Materials Using Low Power Laser Diode and CO2.*International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS Vol: 11 No: 06

Çaydaş, U., &Hasçalık, A. (2008).*Use of the grey relational analysis to determine optimum laser cutting parameters with multi-performance characteristics*. Optics & Laser Technology, 40 (7), 987-994

Chaudhari P. S., Prof. Patel D. M., Dr. Juneja J. L. (2012).*Artificial Intelligence apply for prediction of Laser Cutting Process – A review*. International Journal of Engineering Research and Applications (IJERA). Vol. 2, Issue 4

Choudhury, I. A., & Shirley, S. (2010). *Laser cutting of polymeric materials: An experimental investigation*. Optics & Laser Technology, 42 (3), 503-508

Choudhury, I. A., & Shirley, S. (2010). *Laser cutting of polymeric materials: An experimental investigation*. Optics & Laser Technology, 42 (3), 503-508

Chowdhury K., Pratihar D.K. and Pal D.K. (2002). *Multi-objective optimization in turning—using GA algorithm*, Journal of the Institute of Engineers (India), 82, 37–44

Cus F. and Balic J. (2003).*Optimization of cutting process by GA approach*, Robotics and Computer Integrated Manufacturing, 19, 113–121

Deepak, S. S. K. (2012). *Applications of Different Optimization Methods for Metal Cutting Operation–A Review*. Research Journal of Engineering Sciences . Vol. 1(3), 52-58

Dubey, A. K., &Yadava, V. (2008).*Laser beam machining: a review*. International Journal of Machine Tools and Manufacture, 48 (6), 609-628

Dubey, A. K., &Yadava, V. (2008). Laser Beam Machining: A review. International Journal of Machine Tools and Manufacture, 48 (6), 609-628. Elsevier

Eltawahni H. A. , A. G. Olabi, and K. Y. Benyounis, "*Investigating the CO2 laser cutting parameters of MDF wood composite material,*" Optics & Laser Technology, vol. 43, no. 3, pp. 648–659, Apr. 2011

Eltawahni H.A., Olabi A.G., Benyounis K.Y. (2010).*Effect of Process Parameters and Optimization of CO2 Laser Cutting of Ultra High-Performance Polyethylene. Materials and Design* 31 (2010) 4029–4038. Elsevier Ltd.

Eltawahni, H. A., Hagino, M., Benyounis, K. Y., Inoue, T., &Olabi, A. G. (2012).*Effect of CO2 laser cutting process parameters on edge quality and operating cost of AISI316L*. Optics & Laser Technology, 44 (4), 1068-1082

Ghany KA, Newish M. *Cutting of1.2 mm thick austenitic stainless steel sheet using pulsed and CWNd:YAG laser. Journal of Materials Processing Technology* 2005; 168:438–47.

Gok, A., Gologlu, C., Demirci, H. I., & Kurt, M. (2012).*Determination of Surface Qualities on Inclined Surface Machining with Acoustic Sound Pressure*.Strojniškivestnik - Journal of Mechanical Engineering, 58 (10), 587-597

Grzesik W. and Brol S. (2003).*Hybrid approach to surface roughness evaluation in multistage machining processes, Journal of Materials Processing Technology*, 134, 265– 272

Hashmi K., El Baradie M.A. and Ryan M. (1998).*Fuzzy logic based intelligent selection of machining parameter*, Computers and Industrial Engineering, 35 (3–4), 571–574 I N G. Houston 267.

ICS-UNIDO (2008).*Laser Technologies: a step forward for small and medium enterprises.*United Nations Industrial Development Organization and the International Centre for Science and High Technology. Italy

Kar, A., Scott, J.E., Latham, W.P., 1996. *Theoretical and experimental studies of thick-section cutting with a chemical oxygen-iodine laser (COIL).* J. Laser Appl. 8, 125–133

Karatas, C., Keles, O., Uslan, I., &Usta, Y. (2006). *Laser cutting of steel sheets: Influence of workpiece thickness and beam waist position on kerf size and stria formation*. Journal of materials processing technology, 172 (1), 22-29

Kratky, A., Schuöcker, D., &Liedl, G. (2008, October).*Processing with kW fibre lasers: advantages and limits*. In XVII International Symposium on Gas Flow and Chemical Lasers and High Power Lasers (pp. 71311X-71311X). International Society for Optics and Photonics

Krimpenis A. and Vosniakos G.C. (2002).*Optimization of multiple tool NC rough machining of a hemisphere as a genetic algorithm paradigm application*, International Journal of Advanced Manufacturing Technology, 20, 727– 734

Kumar Dubey, A., &Yadava, V. (2008).*Multi-objective optimisation of laser beam cutting process*. Optics & Laser Technology, 40 (3), 562-570

Kurt M, Kaynak Y, Bagci E, Demirer H, Kurt M. *Dimensional analyses and surface quality of the laser cutting process for engineering plastics*. International Journal of Advanced Manufacturing Technology 2009;41 (3–4) 259–67

Lamiki A. et al (2005). *CO2 laser cutting of advanced high strength steels (AHSS).* Applied Surface Science 242 (2005) 362–368

Lee Y.H., Yang B.H. and Moon K.S. (1999). *An economic machining process model using fuzzy non-linear programming and neural network*, International Journal of Production Research, 37 (4), 835–847

Madić, M., Radovanović, M., &Nedić, B. (2012).*Correlation between Surface Roughness Characteristics in CO2 Laser Cutting of Mild Steel*. Tribology in Industry vol. 34, No. 4

Madić, M., Radovanović, M., &Nedić, B. (2012).*Correlation between Surface Roughness Characteristics in CO2 Laser Cutting of Mild Steel*. Tribology in Industry vol. 34, No. 4

Madić, M., Radovanović, M., &Slatineanu, L. (2013).*Surface Roughness Optimization In Co2 Laser Cutting By Using Taguchi Method*. U.P.B. Sci. Bull., Series D, Vol. 75, Iss. 1, Madić, M., Radovanović, M., &Slatineanu, L. (2013).*Surface Roughness Optimization In Co2 Laser Cutting By Using Taguchi Method*. U.P.B. Sci. Bull., Series D, Vol. 75, Iss. 1,

Majumdar, J. D., & Manna, I. (2003).*Laser Processing of Materials*.Sadhana, 28 (3-4), 495-562

Myers, R. H., Montgomey, D. C., and Anderson-Cook, C. M., 2010. *Response Surface Methodology: Process and Product Optimization Using Designed Experiments*, 3rd ed. WILEY.

Nitrogen Applications (2010).*Metal Fabrication: Laser Cutting*. Generon IGS.

Phipon, R., &Pradhan, B. B.(2012). *Control Parameters Optimization of Laser Beam Machining Using Genetic Algorithm*. International Journal of Computational Engineering Research (ijceronline.com) Vol. 2 Issue. 5

Physics and Astronomy department (n.d).*Laser Machining*.Macquarie University.Faculty of science. Sydney, Australia. Retrievef on April 2013 http://physics.mq.edu.au/files/file/Laser%20Machining.pdf

Powell, J., Al-Mashikhi, S. O., Kaplan, A. F. H., &Voisey, K. T. (2011).*Fibre laser cutting of thin section mild steel: An explanation of the 'striation free'effect*. Optics and Lasers in Engineering, 49(8), 1069-1075

Radonjić, P. D. S., Save, S., Čačak, S., Kovač, P. D. P., & Sad, N.(2012). *Defining New Processing Parameters In Laser Cutting.*16th International Research/Expert Conference. Dubai, UAE

Radovanovic, M., &Madic, C. (2011).*Experimental investigations of CO2 laser cut quality: a review.* Nonconventional Technologies Review, 4, 35-42

Rajpurohit S. R., Prof. Patel D.M. (2012). *Striation Mechanism In Laser Cutting* : The Review. International Journal of Engineering Research and Applications (IJERA). Vol. 2, Issue 2

Riveiro, A., Quintero, F., Lusquiños, F., Comesaña, R., &Pou, J. (2011).*Effects of processing parameters on laser cutting of aluminium–copper alloys using off-axial supersonic nozzles*. Applied Surface Science, 257(12), 5393-5397

Riveiro, A., Quintero, F., Lusquiños, F., Comesaña, R., &Pou, J. (2011).*Study of melt flow dynamics and influence on quality for CO2 laser fusion cutting*. Journal of Physics D: Applied Physics, 44(13), 135501

Salem, H. G., Mansour, M. S., Badr, Y., & Abbas, W. A. (2008).*CW Nd: YAG laser cutting of ultra-low carbon steel thin sheets using O2 assist gas*. Journal of materials processing technology, 196(1), 64-72

Samant, A. N., &Dahotre, N. B. (2009).*Laser machining of structural ceramics: a review*. Journal of the European Ceramic Society, 29(6), 969-993

Sathyanarayanan G., Lin I.J. and Chen M. (1992).*Neural network modeling and multi objective optimization of creep feed grinding of super alloys, International Journal of Production Research*, 30(10), 2421–2438

Schrader R.S. (2003). *Optimization of cost and cycle time for multi-pass turning operation using GA*, genetic algorithm at the University of Illinois Fall 2002, Report no 2003010, 205-2065

Shaji S. and Radhakrisnan V. (2003).*Analysis of process parameters in surface grinding with graphite as lubricant based on Taguchi method*, Journal of Material Processing Technology , 1–9

Sharma, A., &Yadava, V. (2012).*Modelling and optimization of cut quality during pulsed Nd: YAG laser cutting of thin Al-alloy sheet for straight profile*. Optics & Laser Technology, 44(1), 159-168

Sharma, A., &Yadava, V. (2012).*Modelling and optimization of cut quality during pulsed Nd: YAG laser cutting of thin Al-alloy sheet for straight profile*. Optics & Laser Technology, 44(1), 159-168

Singh S., Shan H.S. and Pradeep K. (2002).*Parametric optimization of magnetic field assisted abrasive flow machining by the Taguchi method, Quality and Reliability Engineering International*, 18, 273–283

Sivarao, S., Sivakumar, D. M., Yuhazri, Y., Tan, C., &Haeryip, S. (2012). *An Exploratory Study-Critical Laser Processing of Composite Materials*. International Journal of Engineering Research & Technology, 1(10), 1-8

Sivarao, T. J. S., &Ammar, S (2010).*RSM Based Modeling for Surface Roughness Prediction in Laser Machining.* International Journal of Engineering & Technology IJET-IJENS Vol: 10 No: 04

Sommer, C.(2009), *Non-Traditional Machining Handbook*, Advance Publishing,

Sparkes M., Gross M., Celotto S., Zhang T., and O'Neill W. *Practical and theoretical investigations into inert gas cutting of 304 stainless steel using a high brightness fiber laser,* Journal of Laser Applications, 2008, 20, pp. 59-67

Stournaras, A., Stavropoulos, P., Salonitis, K., &Chryssolouris, G. (2009).*An investigation of quality in CO< sub> 2</sub> laser cutting of aluminum*. CIRP Journal of Manufacturing Science and Technology, 2(1), 61-69

Syn, C. Z., Mokhtar, M., Feng, C. J., &Manurung, Y. H. (2011).*Approach to prediction of laser cutting quality by employing fuzzy expert system*. Expert Systems with Applications, 38(6), 7558-7568

Tezuka, S., Tokura, H., & Yoshikawa, M., 2005. *Cutting Of Diamond Grit With YAG Laser* [pdf] Available at: <http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA206954> [Accessed 20 August 2013].

Tulasiramarao, B., Srinivas, K., Reddy, P. R., Raveendra, A., & Ravi, B. *Effect of Processing Parameters on Surface Finish of the Components Processed By CNC Turning Machine*. International Journal of Mechanical Engineering applications Research – IJMEAR.Vol 04, Issue 01

University of Bradford.*Response Surface Methodology*.Book chapter. Retrieved

Wandera, C. (2010). *Performance of high power fibre laser cutting of thick-section steel and mediumsectionaluminium*.PhD thesis. Lappeenranta University of Technology, Finland

Yilbas, B. S. (2008). *Laser cutting of thick sheet metals: Effects of cutting parameters on kerf size variations. Journal of materials processing technology*, 201(1), 285-290

Yilbas, B. S., Karatas, C., Uslan, I., Keles, O., Usta, Y., Yilbas, Z., &Ahsan, M. (2008). *Wedge cutting of mild steel by CO laser and cut-quality assessment in relation to normal cutting.* Optics and Lasers in Engineering, 46(10), 777-784